

**Maintenance Practices —
Improving Sustainability Performance of
Existing Office Buildings:
An Australian Case Study**

Dinh Manh Nguyen
BCE, MPD

A thesis submitted in fulfilment of the requirements
for the award of Doctor of Philosophy of the
University of Technology Sydney
June, 2017

Certificate of Original Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This research is supported by an Australian Government Research Training Program Scholarship.

Production Note:

Signature of Student: Signature removed prior to publication.

Date: 29 June 2017

Acknowledgments

Many people have helped and guided me through my doctoral thesis at the University of Technology Sydney. I am grateful to them all, many thanks and more.

Many thanks to my supervisors Associate Professor Grace Ding and Adjunct Professor Goran Runeson for their overall support and assistance with the doctoral research process, it is much appreciated. Special thanks to Dr Narelle Smith for her comments and advice on my questionnaire design and Mr Paul Van der Kallen for his assistance in the organisation of the focus group discussion.

Many thanks also to my colleagues in the School of the Built Environment, Faculty of Design, Architecture and Building for their comments and advice during my survey process; to the RICS Oceania Head Office for providing me with the venue to conduct the focus group discussion; to AMP Capital for providing me with the data and information for the case studies; to the institutes of AIQS, API, CIOB, FMA and RICS for assisting me with the follow-up of participants and to all those who participated in the questionnaire survey, focus group discussion and Delphi study for this research.

Ms Susie Walsh is gratefully acknowledged for her valued editorial assistance.

Further, to my lovely wife and children, who always encouraged and supported me to undertake the degree. Especially, to my lovely wife, Thi Phung Nguyen, who has made a great many sacrifices for me and our family.

Finally, I would like to dedicate my achievement to my deceased father, who always taught me: *Vouloir c'est pouvoir*, “Where there is a will, there is a way”.

Table of Contents

| | |
|--|-----------|
| Certificate of Original Authorship | ii |
| Acknowledgments | iii |
| Table of Contents | iv |
| List of Figures..... | vii |
| List of Tables | viii |
| List of Abbreviations | x |
| Abstract..... | xiv |
| 1. Introduction | 1 |
| 1.1 Research Background..... | 1 |
| 1.2 Research Significance..... | 3 |
| 1.3 Research Gaps..... | 5 |
| 1.4 Research Aims and Objectives | 6 |
| 1.5 Research Questions..... | 7 |
| 1.6 Research Methodology | 10 |
| 1.7 Thesis Structure..... | 14 |
| 2. Office Buildings and the Environment..... | 19 |
| 2.1 Introduction | 19 |
| 2.2 An Environmental Crisis | 19 |
| 2.3 International Collaboration in Climate Change..... | 27 |
| 2.4 Impacts of Office Buildings on the Environment..... | 31 |
| 2.5 Summary..... | 45 |
| 3. Sustainable Maintenance of Office Buildings | 46 |
| 3.1 Introduction | 46 |
| 3.2 Sustainable Development of Existing Buildings | 46 |
| 3.3 Office Building Maintenance..... | 55 |
| 3.4 Improving Office Buildings with Sustainable Practices in Australia | 61 |

| | | |
|-----------|---|------------|
| 3.5 | <i>Summary</i> | 82 |
| 4. | Life Cycle Perspectives in Assessment of Building Performance | 84 |
| 4.1 | <i>Introduction</i> | 84 |
| 4.2 | <i>Life Cycle Approach</i> | 86 |
| 4.3 | <i>Environmental Assessment</i> | 98 |
| 4.4 | <i>Economic Assessment</i> | 105 |
| 4.5 | <i>Combining Environmental and Economic Approaches for Assessing Performance of Existing Office Buildings</i> | 114 |
| 4.6 | <i>Summary</i> | 125 |
| 5. | Research Design..... | 126 |
| 5.1 | <i>Introduction</i> | 126 |
| 5.2 | <i>Research Methodology</i> | 126 |
| 5.3 | <i>Research Design</i> | 134 |
| 5.4 | <i>Summary</i> | 150 |
| 6. | Data Collection and Analysis | 151 |
| 6.1 | <i>Introduction</i> | 151 |
| 6.2 | <i>Questionnaire Survey Process</i> | 151 |
| 6.3 | <i>Focus Group</i> | 173 |
| 6.4 | <i>Delphi Study</i> | 178 |
| 6.5 | <i>Outcomes of Studies</i> | 190 |
| 6.6 | <i>Summary</i> | 195 |
| 7. | Model Development and Testing..... | 197 |
| 7.1 | <i>Introduction</i> | 197 |
| 7.2 | <i>Development of the Model of Sustainable Maintenance of Office Buildings (SMOB)</i> | 197 |
| 7.3 | <i>Explanation of the SMOB</i> | 204 |
| 7.4 | <i>Estimating Annual Costs and Potential Savings in the SMOB for Existing Office Buildings</i> | 217 |
| 7.5 | <i>Summary</i> | 232 |
| 8. | Case Studies and SMOB Verification..... | 233 |
| 8.1 | <i>Introduction</i> | 233 |

| | | |
|--------------|--|------------|
| 8.2 | <i>The Case Studies</i> | 234 |
| 8.3 | <i>Case Study Buildings</i> | 235 |
| 8.4 | <i>Further Potential Savings for the Case Study Buildings Using the SMOB</i> | 246 |
| 8.5 | <i>Potential Savings for the Case Study Buildings in Expected Increase of Energy Price</i> | 263 |
| 8.6 | <i>Summary</i> | 268 |
| 9. | Summary and Conclusions | 270 |
| 9.1 | <i>Introduction</i> | 270 |
| 9.2 | <i>Research Overview</i> | 270 |
| 9.3 | <i>Contributions to Knowledge</i> | 275 |
| 9.4 | <i>Limitations of the Research</i> | 277 |
| 9.5 | <i>Research Findings</i> | 278 |
| 9.6 | <i>Recommendations for Further Research</i> | 286 |
| 9.7 | <i>Conclusion</i> | 291 |
| Appendix 1-1 | Sustainable Maintenance of Office Buildings Pilot Survey | 293 |
| Appendix 1.2 | Sustainable Maintenance of Office Buildings Main Survey | 302 |
| Appendix 2.1 | Mean Difference Tests for Six Questions of Survey Question 1.7 | 313 |
| Appendix 2.2 | Mean Difference Tests for Three Questions of Survey Question 1.7 | 325 |
| Appendix 2.3 | Mean Difference Tests for Six Questions of Survey Question 1.8 | 337 |
| Appendix 2.4 | Mean Difference Tests for Six Questions of Survey Question 1.9 | 341 |
| Appendix 3.1 | SMOB Calculations – Costs and Savings on Upgrading | 345 |
| Appendix 3.2 | SMOB Calculations – Savings on Routine and Ad Hoc Maintenances | 347 |
| | References | 348 |

List of Figures

| | | |
|------------|--|-----|
| Figure 1.1 | Research plan | 12 |
| Figure 1.2 | Thesis structure | 18 |
| Figure 2.1 | Global annual mean temperature anomalies | 21 |
| Figure 2.2 | Australian annual average number of hot days per decade for the period 1960 to 2010..... | 22 |
| Figure 2.3 | Interactions between buildings and the environment | 32 |
| Figure 2.4 | Summary of buildings links to emissions over life cycle phases | 33 |
| Figure 2.5 | Energy used in delivering surface water supply in Australia | 41 |
| Figure 2.6 | Greenhouse gas intensity of electricity supply by Australian states in 2009 | 43 |
| Figure 3.1 | Energy components and emissions of a building over its lifetime | 56 |
| Figure 3.2 | Energy end use shared in Sydney office buildings..... | 68 |
| Figure 3.3 | Waste disposal management plan | 79 |
| Figure 4.1 | An LCA framework | 101 |
| Figure 4.2 | Optimisation LCC for upgrading a building or system | 109 |
| Figure 4.3 | Potential costs and savings relationship in performing LCC | 111 |
| Figure 4.4 | A suggestion of combined assessment process using LCA and LCC | 119 |
| Figure 4.5 | Types of data for LCA of existing office buildings | 120 |
| Figure 5.1 | Research process | 140 |
| Figure 5.2 | Three stages of outcomes for the development of the SMOB | 148 |
| Figure 7.1 | Model of sustainable maintenance of office buildings (SMOB)..... | 200 |
| Figure 7.2 | Extension of the SMOB | 203 |
| Figure 7.3 | Impact of automatic dimming control lighting on annual energy consumption for atrium lighting..... | 210 |
| Figure 7.4 | Annualised capital costs and savings in upgrading over a 30-year period based on SMOB | 223 |
| Figure 7.5 | Annual costs and savings in upgrading for water efficiency based on SMOB | 228 |
| Figure 8.1 | Potential annual savings in upgrading for Building 1 using the SMOB | 253 |
| Figure 8.2 | Potential annual savings in upgrading for Building 2 using the SMOB | 257 |
| Figure 8.3 | Potential annual savings in upgrading for Building 3 using the SMOB | 261 |
| Figure 8.4 | Potential savings in upgrading or improving for the three case building in expected energy price increased by 10%..... | 267 |

List of Tables

| | | |
|-----------|---|-----|
| Table 2.1 | Greenhouse gas emissions influenced by human activities..... | 26 |
| Table 2.2 | Commitments of countries in reducing emissions | 29 |
| Table 2.3 | Summary of distribution of life cycle environmental burden for five impact categories of buildings | 34 |
| Table 2.4 | Impacts of building on global resources and pollution | 35 |
| Table 2.5 | The shared end use of energy and greenhouse gas emissions of Australian office buildings..... | 37 |
| Table 2.6 | Embodied energy content and embodied emissions of common building materials..... | 38 |
| Table 2.7 | Water levels stored in dams in Australia's capital cities in May 2007 | 40 |
| Table 3.1 | Drivers for sustainable building development..... | 54 |
| Table 3.2 | Renovation criteria for sustainable maintenance of office buildings | 66 |
| Table 3.3 | End use of water in a typical office building..... | 74 |
| Table 3.4 | Water savings of modelled opinions compared to conventional office buildings.. | 75 |
| Table 3.5 | Energy consumption to produce potable water in plant life cycle steps | 76 |
| Table 3.6 | Contribution of primary energy demand and CO ₂ emissions associated with the manufacture of some building materials by 1 m ² GFA..... | 77 |
| Table 4.1 | Benefits of retaining and improving an existing office building with sustainable maintenance..... | 90 |
| Table 4.2 | Study period for energy use in office buildings | 95 |
| Table 4.3 | Life span of components and services systems for office buildings | 97 |
| Table 4.4 | Differences in purpose and approach between LCA and LCC | 115 |
| Table 5.1 | Strengths and weaknesses of quantitative methods..... | 129 |
| Table 5.2 | Strengths and weaknesses of qualitative methods..... | 131 |
| Table 5.3 | Features of quantitative, qualitative and mixed method..... | 134 |
| Table 5.4 | Four stages of data collection..... | 138 |
| Table 5.5 | Characteristics, strengths and weaknesses of the Delphi method | 145 |
| Table 6.1 | Responses by category of respondents..... | 156 |
| Table 6.2 | Characteristics of respondents..... | 158 |
| Table 6.3 | Respondents working directly in the maintenance of office buildings | 159 |
| Table 6.4 | Outcomes of mean different tests between groups of respondents | 159 |
| Table 6.5 | Rating of issues regarding strategies for sustainable maintenance practices | 161 |
| Table 6.6 | Rating of factors that influence the current uptake of sustainability initiatives in office buildings..... | 163 |
| Table 6.7 | Rating of factors in performing sustainable maintenance of office buildings..... | 164 |

| | | |
|------------|---|-----|
| Table 6.8 | Summary of difficulties perceived by key stakeholders | 166 |
| Table 6.9 | Current maintenance practices in office buildings | 168 |
| Table 6.10 | Critical issues in achieving sustainable maintenance of office buildings | 170 |
| Table 6.11 | Critical issues in developing sustainable maintenance practices | 172 |
| Table 6.12 | Categories of participants in the focus group discussion | 173 |
| Table 6.13 | Outcomes of focus group discussion..... | 175 |
| Table 6.14 | Timeframe of the Delphi study | 179 |
| Table 6.15 | Participants in the Delphi study | 182 |
| Table 6.16 | 16 critical issues compiled from Round 1 | 184 |
| Table 6.17 | 16 critical issues rated from Round 2..... | 187 |
| Table 6.18 | 12 most critical issues rated from Round 3 | 189 |
| Table 6.19 | 12 critical issues in sustainable maintenance of office buildings resulting from survey, focus group and Delphi study | 191 |
| Table 7.1 | Annual costs and savings in SMOB over a 30-year period..... | 218 |
| Table 7.2 | Calculation on savings of some major systems in the SMOB | 220 |
| Table 7.3 | Calculation on savings of water systems in the SMOB | 226 |
| Table 8.1 | Characteristics of the three case study buildings..... | 238 |
| Table 8.2 | Annual savings realised by the SMOB from current maintenance practices for the three case study buildings | 240 |
| Table 8.3 | Convert of water usages to energy consumptions and CO ₂ emissions of the three case study buildings | 244 |
| Table 8.4 | Potential further annual savings using SMOB in upgrading or improving for the three case study buildings | 248 |
| Table 8.5 | Potential annual savings in upgrading or improving for the three case study buildings using the SMOB | 262 |
| Table 8.6 | Potential savings with an expected increase of energy price by 10% using the SMOB | 264 |

List of Abbreviations

| | |
|--------------------|---|
| ABARES | Australian Bureau of Agricultural and Resource Economics and Sciences |
| ACT | Australian Capital Territory |
| A ₀ | Annual amount |
| AIQS | Australian Institute of Quantity Surveyors |
| AMCA | Air Conditioning and Mechanical Contractors Association |
| AP | Acidification potential |
| API | Australian Property Institute |
| AR4 | Fourth Assessment Report |
| ASHRAE | American Society of Heating, Refrigerating and Air Conditioning Engineers |
| AS/NZS | Australia/New Zealand Standards |
| ASTM | American Society for Testing and Materials Publications |
| Australia ICOMOS | Australia International Council of Monument and Site |
| AWC | Available Water Capacity |
| BAU | Business as Usual |
| BEEC | Building Energy Efficiency Certificate |
| BMCS | Building management and control systems |
| BMRC | Bureau of Meteorology Research Centre |
| BOMA | Building Office and Managers Association |
| BPI | Building price index |
| BWRO | Brackish water reverse osmosis |
| CAR | Cause, Action, and Result |
| CBD | Commercial Building Disclosure |
| CBDs | Central business districts, e.g. Sydney CBD |
| CEC | Commission for Environmental Cooperation |
| CEO | Chief executive officer |
| CEPA | Commonwealth Environment Protection Agency |
| CFCs | Chlorofluorocarbons |
| CH ₄ | Methane |
| CIE | Centre for International Economics |
| CIOB | Chartered Institute of Building |
| CO ₂ | Carbon dioxide |
| CO ₂ -e | Carbon dioxide equivalent |

| | |
|------------------|--|
| COAG | Council of Australian Governments |
| COP21 | 21 st Conference of the Parties |
| COP | Coefficient of Performance |
| CPI | Consumer Price Index |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| EE | Energy efficiency |
| ERI | Energy Recovery Inc. |
| ESCOs | Energy service companies |
| ESD | Ecologically sustainable development |
| FMA | Facility Management Association of Australia |
| GFA | Gross floor area |
| GHG | Greenhouse gas |
| GL | Gigalitre |
| GST | Goods and services tax |
| Gt | Gigatonne |
| GWh | Gigawatt hour |
| GWP | Global warming potential |
| H ₂ O | Water vapour |
| HCFCs | Hydrochlorofluorocarbons |
| HFCs | Hydrofluorocarbons |
| HVAC | Heating, ventilation, and air conditioning |
| IEA | International Energy Agency |
| IEC | International Electrotechnical Commission |
| IEQ | Indoor environment quality |
| IPCC | Intergovernmental Panel on Climate Change |
| IRR | Internal rate of return |
| ISO | International Organisation for Standardisation |
| kWh | Kilowatt hour |
| LCA | Life cycle assessment |
| LCC | Life cycle costing |
| LCE | Life cycle energy |
| LCI | Life cycle inventory |
| LCIA | Life cycle impact assessment |
| LE | Lighting efficiency |
| LED | Light-emitting diode |
| LPP | Litres per person |

| | |
|------------------|---|
| MEPS | Minimum efficiency performance standards |
| MF | Microfiltration |
| MJ | Megajoule |
| MIT | Massachusetts Institute of Technology |
| ML | Megalitre |
| MPa | Megapascal |
| MR | Materials and resources |
| NABERS | National Australian Built Environment Rating System |
| NASA | National Aeronautics and Space Administration |
| NF | Nanofiltration |
| NLWRA | National Land and Water Resources Audit |
| NP | Nutrication potential |
| NPV | Net present value |
| NS | Norway standards |
| NSW | New South Wales |
| NT | Northern Territory |
| N ₂ O | Nitrous oxide |
| OEH | Office of Environment and Heritage (NSW) |
| OECD | Organisation for Economic Co-operation and Development |
| ODP | Ozone depletion potential |
| PCA | Property Council of Australia |
| PECC | Special Program on Climate Change |
| PFCs | Perfluorocarbons |
| PJ | Petajoule |
| PVC | Polyvinyl chloride |
| QLD | Queensland |
| RH | Relative humidity |
| RICS | Royal Institute of Chartered Surveyors |
| SA | South Australia |
| SADPTI | South Australia Department of Planning Transport and Infrastructure |
| SBS | Sick building syndrome |
| SD | Standard deviation |
| SIR | Savings to investment ratio |
| SMOB | Sustainable Maintenance of Office Buildings |
| SPSS | Statistical Package for the Social Sciences |
| SPV | Single present value |

| | |
|--------|---|
| SVOCs | Semi volatile organic compounds |
| SWRO | Sea water reverse osmosis |
| T5 | Fluorescent lamps T5 |
| T8 | Fluorescent lamps T8 |
| TAS | Tasmania |
| TBL | Triple bottom line |
| UF | Ultrafiltration |
| UK | United Kingdom |
| UNFCCC | United Nations Framework Convention on Climate Change |
| UPV | Uniform present value |
| US | United States of America |
| VAV | Variable air volume |
| VIC | Victoria |
| VCT | Vinyl composition tile |
| VOCs | Volatile organic compounds |
| VSD | Variable speed drives |
| WA | Western Australia |
| WD | Waste disposal management |
| WE | Water efficiency |
| WWR | Window to wall ratio |

Abstract

The purpose of this thesis is to establish a method to analyse the interaction between the environment and existing buildings, to examine how the impact of existing buildings on the environment can be reduced and to suggest strategies by which any negative effects can be minimised. The investigation is focused on the development of a strategic framework to maintain and improve existing office buildings performance through sustainable maintenance strategies. It concentrates on reducing emissions generated within office buildings over their life cycle. The developed framework is a model for sustainable maintenance of office buildings entitled SMOB: an Australian case study.

Over many decades, office buildings have been recognised as a significant area contributing to the negative impacts on the environment over their life cycle, hastening climate change or global warming. In return, climate change also impacts on buildings with extreme heatwaves occurring more frequently and raising the earth's temperature. Increased temperatures make many advanced techniques as applied in buildings ineffective, which then require more energy to provide indoor comfort. The operation and maintenance phase is the longest period of operation over a building's life span. In this period, office buildings consume the highest rates of energy and water; and consequently, emit the highest rates of greenhouse gas pollution, especially CO₂, into the environment.

The framework of SMOB includes four indicators and 23 criteria for scheduling sustainable building maintenance through routine, ad hoc and upgrading practices which are derived from analysis of data collected through questionnaire survey, focus group discussion and a Delphi study. Case studies were used to verify the SMOB and results show that when using the model, energy and water consumption, and in particular CO₂ emissions in the buildings are significantly reduced, and that the buildings will satisfy environmental protection requirements. The research shows that the SMOB is well suited for assessing the costs and returned benefits against economic and environmental criteria in sustainable office building maintenance.